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PATT2
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APPLICATION FOR TELESCOPE TIME (OPTICAL AND INFRARED)

1 TELESCOPE *(AAT, UKST, WHT, INT or UKIRT)*	WHT	Reference: W/2017B/20 Date stamp:	15 Mar 2017
2 SEMESTER	2017B	3 SCIENTIFIC CATEGORY	1

4 COORDINATED PATT PROPOSALS — *AAT:* ☐ *UKST:* ☐ *WHT:* ☒ *INT:* ☐ *UKIRT:* ☐ *JCMT:* ☐ *GEMINI:* ☐ *LT:* ☐ *MERLIN:* ☐

5 PRINCIPAL APPLICANT

Surname: Hooton Title: Mr First name: Matthew
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6 COLLABORATORS

Name:	Institute:	Observer?
Dr. Chris Watson	Queen's University Belfast	Yes
Dr. Ernst de Mooij	Dublin City University	Yes
Dr. Neale Gibson	Queen's University Belfast	Yes
Andrew Thompson	Queen's University Belfast	Yes

7 SHORT TITLE OF PROPOSAL *(maximum 12 words)*

Near-infrared secondary eclipses of the highly irradiated exoplanet KELT-16b

8 SUMMARY OF PROPOSED OBSERVATIONS

KELT-16b is a recently discovered hot Jupiter, and one of less than ten known to date with a period under a day. The combination of its small orbital separation and its bright host star makes it a terrific candidate for atmospheric categorisation, and is likely to be high up on JWST's target list. We propose to use LIRIS to measure the J-, H- and K_s- band secondary eclipse depths of KELT-16b, which will allow us to probe the peak of its thermal emission spectrum. This will allow us to place important constraints on its atmospheric composition and provide information on the temperature-pressure profile, from which direct comparisons can be made to WASP-43b, a smaller, cooler analog of KELT-16b. This in turn will allow us to test the main theories in literature regarding temperature inversions in the upper atmospheres of hot Jupiters.

9 FOCAL STATION, INSTRUMENT AND DETECTOR

Focal station:	Instrument:	Detector(s):	Gratings/Filters:
Cassegrain	LIRIS	HgCdTe Hawaii	J, H, K_s

10 OBSERVING TIME REQUESTED THIS SEMESTER

	Dark:	Grey:	Bright:	specify nights *or* weeks:
Time requested this semester			6	N
Minimum useful allocation this semester			3	

UKIRT applicants requiring dark time must justify this in section 18

11 COMPLETE THIS SECTION ONLY IF THIS IS A LONG TERM PROPOSAL

	Dark:	Grey:	Bright:	specify nights *or* weeks:
Total time requested				

Justification for long term status must be given in section 17

Text fonts must *not* be smaller than the style-file defaults

12 SCHEDULING INFORMATION

Preferred dates:	Time critical - dates of secondary eclipses given below.
Impossible dates: *Give justification for impossible dates*	All others not outlined in 'Any other scheduling constraints' below. No secondary eclipses visible.
If observations are to be simultaneous with other telescopes or satellites, give details:	
Any other scheduling constraints: *Include likely clashes with other time applications, constraints on lunar position or quarter, instrument preparation requirements, etc*	Below we give list the nights on which a secondary eclipse of KELT-16b is visible from La Palma. Note that the dates are for the start of the night. August 3, 4, 5, 6, 7, 8 & 9; September 5, 6, 7, 8, 9 & 10; October 10 & 11

13 SERVICE OBSERVING

yes: [ ] no: [x] maybe: [ ]

14 SUPPORT ASTRONOMER REQUESTED AT TELESCOPE

every night: [ ] no: [ ] first night only: [x]

15 LIST OF PRINCIPAL TARGETS

Object(s):	RA(h,m):	Dec(degs):	Mag(type):	Colour:	Exp. Time:
	(2000)	(2000)	V	V-K	(s)
KELT-16b	20 57 04.435	+31 39 39.57	11.90	1.26	7

16 LIST ALL SIMILAR/SUPPORTING APPLICATIONS TO ANY PATT OR OTHER TIME ASSIGNMENT COMMITTEE

You must include a brief description of any other applications whose targets or science goals are similar to those requested here

Telescope/satellite:	Title/Description of programme:
INT	"Probing the thermal emission of KELT-16b in the i- and Z-band". Related proposal to use WFC to measure the i- and Z- band secondary eclipse depths. This will probe the planet's spectral energy distribution in the Wien limit, and provides an important discriminatory point to measure the C/O ratio of the planet. We note that both proposals are still scientifically valuable independent of each other, but the best constraints on the atmospheric composition will come from combining the i, Z, J, H and K_s secondary eclipse measurements.

THE TARGET – KELT-16b is a newly discovered hot Jupiter (HJ) whose ultra-short orbital period (P = 23.3 hr) puts it very close to being tidally disrupted. To date it is one of only a handful of HJs with an orbital period under one day. The combination of its small orbital separation, its hot host star and its large radius makes it one of the best known candidates for atmospheric categorisation, and is very likely to be target for follow-up observations with JWST. KELT-16b provides us with a unique opportunity not only to study the extreme environment in which it resides, but also to detect thermal emission at wavelengths not possible for the vast majority of exoplanets. KELT-16b is also the planet that telescope schedulers dream of, due to the fact that its orbital period of just under one sidereal day means that eclipses can observed on up to five consecutive nights.

BACKGROUND – Soon after the initial detections of planetary thermal emission, temperature inversions were reported in the atmospheres of numerous HJs, including HD 209458b, HD 149026b and TrES-2b. Since these initial reports, numerous models have been proposed to explain the sources that give rise to such inversions. Hubeny et al. (2003) predicted that the strongly absorbing compounds TiO and VO could be present in appreciable quantities in the upper atmospheres of HJs, and Fortney et al. (2008) proposed that TiO and VO, and consequently inversions, would only be present in the atmospheres of the most highly irradiated hot Jupiters. Subsequent observations have not supported this model, most notably of WASP-12b, for which no inversion has been observed despite its 0.02 AU separation from a G0 type star. Knutson et al. (2010) proposed that inversions are not present in HJs orbiting highly active stars as the TiO and VO compounds in the upper atmosphere are destroyed due to the higher levels of stellar activity, with the opposite true of less active stars. This theory was supported by observations of an inversion in HD 209458b and a lack of one in HD 189733b, however, subsequent observations challenged this theory. For example, there was no observed inversion in the ever-problematic WASP-12b despite its inactive host. Madhusudhan (2012) proposed that planets with a C/O ratio above 1 have most of their oxygen bound up in CO molecules, hence suppressing the amount of atmospheric TiO and VO, and therefore the planet's ability to host an inversion, with the opposite true for C/O < 1. This theory fits observations of WASP-12b and WASP-19b (Burton, Watson, Gibson et al, 2012), for which high C/O ratios have been inferred and are highly irradiated by their host stars. On top of these, new observations and reanalyses of old data have cast doubt on most reported thermal inversions, with models without inversions fitting the data as well as those with. The ability to observe the thermal emission from newly discovered ultra-short period HJs will act to test the validity of the above theories further.

OBJECTIVES – We propose to observe the secondary eclipses of KELT-16b in J-, H- and K_s- bands, using LIRIS. This will enable us to measure the the temperature at the atmospheric depths probed by each of these bands, which combined with INT i- and Z-band data will allow us to build up a detailed temperature-pressure profile of the upper atmosphere. This information will be used to infer whether or not a thermal inversion is present at these depths, and test the validity of each of the theories listed above. Measurement of the thermal emission in these bands will also probe the spectral energy distribution at and redward of the peak of its thermal emission, in doing so quantifying the majority of the emitted energy of the planet. Spectral features present in these bands include those of water, methane and carbon-monoxide, allowing us to constrain the chemical composition.
KELT-16b provides such a unique opportunity as it is one of the few known exoplanets where the measurement of thermal emission in the full set of bands listed above is indeed possible with current technology. Such measurements for KELT-16b will add it to a small list planets for which the same measurements have been made, which thus far have produced wide-ranging compositions and temperature-pressure profiles. Of particular interest will be the opportunity to draw direct comparisons to WASP-43b, a cooler and less massive analog of KELT-16b with an atmosphere best fit by models where temperature monotonically decreases with pressure. Results for these planets can then in turn be directly compared to significantly less dense planets including WASP-12b and WASP-19b, to see what effects planetary density has on atmospheric composition and temperature-pressure profiles.

18 TECHNICAL INFORMATION (I)

Give details of the technical feasibility of the proposal (S/N,etc) AND any non-standard technical requirements

As we intend to use LIRIS to measure two secondary eclipse depths of KELT-16b in J-, H- and K_s-bands, we require a total of six nights, (2 per eclipse). We request two secondary eclipse observations per band in order to help reduce the impact of systematics that can affect high-precision exoplanet studies.

STRATEGY – For these observations we will use the same strategy as used for the GROUSE project (see e.g. De Mooij et al. 2011, 2013). This involves defocussing the telescope and observing the target in staring mode. In doing so, the flux from the target is spread over a greater number of pixels, allowing longer exposures to be taken while keeping the flux in the linear regime of the detector. Spreading the light over many pixels also reduces the impact of any residual pixel-to-pixel variations not removed by the flat-field, which in turn improves the stability of the lightcurve. We will also keep the target at the same position on the detector for the entirety of the observations, in doing so improving the stability of the lightcurve further. The use of staring mode will increase the efficiency of the observations, as no telescope moves have to be performed. Whilst this makes the sky-subtraction necessary at these wavelengths more difficult, we will acquire dithered sky-frames before and after the eclipse observations to construct a background map that can be subtracted from the science frames.

SIGNAL TO NOISE CONSIDERATIONS – For these observations we will use an exposure time of ∼7 seconds; since we will use staring mode, the overheads should be negligible, and we therefore expect to obtain more than 1100 frames during eclipse. In addition to the eclipse, we will observe an out-of-eclipse baseline. This baseline is very important, since it will set the level with respect to which the eclipse is measured, and can also be used to correct for systematic effects and estimate the impact of red-noise on the data.

From experience, we expect to reach a signal-to-noise per frame of ∼250. This estimate includes all the systematic effects. We will therefore be able to reach a 5σ limit on the eclipse of 0.6 mmag. The minimum expected eclipse depths (for a homogeneous temperature on the day- and night-side) are 0.6, 1.0 and 1.5 mmag in J, H and K, respectively – while for instant re-radiation, the eclipse depths will be 1.6, 2.3 and 3.0 mmag in the same bands. We will therefore be able to detect the eclipse of KELT-16b in all three bands.

TIME REQUEST AND SCHEDULING REQUIREMENTS – We require ∼5 hours of comtemporary out-of-eclipse light each night to set the baseline against which the secondary eclipse depths will be measured, as well as to help detrending. This then amounts to a request of 7.5 hours per eclipse (the eclipse duration is 149 minutes), essentially 1 night per eclipse. As we wish to measure the eclipse twice in 3 different wavelength bands (J-, H- and K_s-), this motivates our request of 6 nights in total.

Below we give the dates on which a secondary eclipse of KELT-16b is visible from La Palma. Note that these dates are for the start of the night.

August 3, 4, 5, 6, 7, 8 & 9
September 5, 6, 7, 8, 9 & 10
October 10 & 11

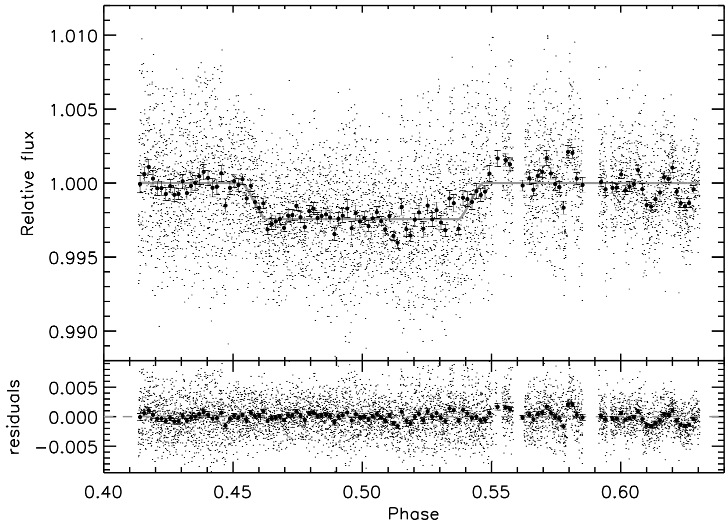

Figure 1: LIRIS K_s-band secondary eclipse lightcurve for WASP-33b adapted from De Mooij et al. (2013 - team member). This lightcurve demonstrates the capabilities of LIRIS to characterise atmospheres in the near-infrared.

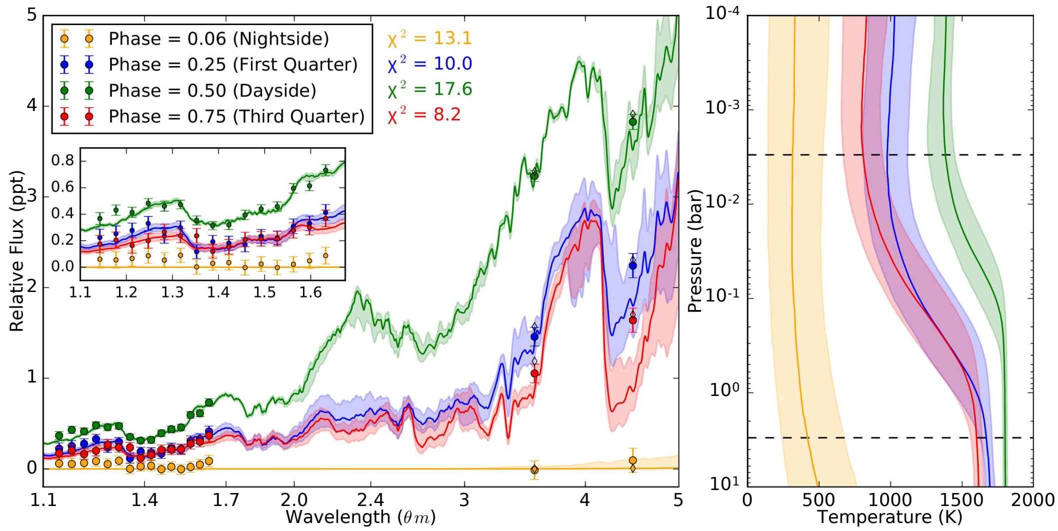

Figure 2: Emission spectra (left) and thermal profiles (right) of WASP-43b at four orbital phases, taken from Stevenson et al. (2017). The data are a combination of Spitzer and Hubble observations, with median models with 1σ uncertainties. Our observations will probe the thermal emission of KELT-16b from $\sim$1.1 – $\sim$2.3 μm, allowing us to further constrain the chemical composition and temperature structure of its atmosphere. The J, H and K_s data enable the impact of different chemistries (such as water, carbon monoxide, carbon dioxide and methane) on the thermal emission to be studied and are complementary to the i- and Z-band WFC observations requested in a separate proposal.

REFERENCES

De Mooij et al., (2013), A&A, 550, 54
Fortney et al., (2008), ApJ, 678, 1419
Hubeny et al., (2003), ApJ, 594, 1011
Knutson et al., (2010), ApJ, 720, 1569
Madhusudhan et al., (2010), Nature 469, 64
Madhusudhan, (2012), ApJ, 758, 36
Oberst et al., 2017, AJ 153, 97
Stevenson et al., 2017, AJ 153, 68

19 SUMMARY OF BACKUP PROGRAMME FOR POOR OBSERVING CONDITIONS

If instrumentation or setup differs from main programme, give full details

Due to our strategy of defocussing the telescope, these observations are fairly robust against poor seeing conditions.

20 RELATED PATT APPLICATIONS OVER THE LAST FOUR SEMESTERS *(including unsuccesful applications)*

PATT reference:	Award:	Clear nights:	Comments:
I/2016B/P6	9 nights	1 night	Of the 9 allocated nights, only 1 night provided useful data. Two nights were strongly affected by clouds and the remainder were completely lost due to weather.
I/2017A/P12	9 nights		Scheduled for observation in July
W/2017A/P34	ToO		No observations triggered

21 PUBLICATIONS BASED ON PATT TIME PUBLISHED DURING THE LAST FOUR SEMESTERS *(maximum 6)*

Barros et al., (2016), A&A, 593, 113, "WASP-113b and WASP-114b, two inflated hot Jupiters with contrasting densities" (LT+RISE)

Burton, Watson et al., (2015), MNRAS, 446, 1071, "Defocused transmission spectroscopy: a potential detection of sodium in the atmosphere of WASP-12b" (WHT+ISIS)

22 EXPERIENCE OF INTENDED OBSERVERS WHO HAVE NOT PREVIOUSLY USED THIS TELESCOPE

All investigators on this proposal are highly experienced with high-precision photometry. De Mooij was part of the team that carried out the first ever ground-based detection of a secondary eclipse. Gibson led the team which detected the first K band secondary eclipse of WASP-19b (see Gibson et al. 2010). Watson was part of the team to detect the first z'-band secondary eclipse detection of WASP-19b (the 3rd ground-based z'-band detection in the world at the time - see Burton et al. 2012)

23 COMPLETE IF THE OBSERVATIONS ARE PRIMARILY FOR A STUDENT RESEARCH TRAINING PROGRAMME

Name of student:	Matthew Hooton
Project title:	Characterising the atmospheres of extrasolar planets

24 COMPLETE IF THE OBSERVATIONS ARE ASSOCIATED WITH A CURRENT STFC RESEARCH GRANT

Name of principal investigator:	
Grant title:	
Grant number:	

25 NON-STANDARD TRAVEL AND SUBSISTENCE REQUIREMENTS *(UK observers only)*

Justify requests for travel and subsistence for more than one person:

Details of any other expenditure (eg freight, remote observing):